ending element of the univels is reached where $y = y_n$. Although the integer steps are described herein as positive 1, it should be appreciated that the integers can be negative and can be in other logical values. It should also be appreciated that the integer values that are stored need not correspond to centered values along the primary direction of movement. It is just that the centered values provide the most representative sampling along the particle track.

Having stepped to a "next" univel at step 170, it is determined, at step 172, whether any of the error terms exceed the threshold value. If the error terms do not exceed the threshold values, a determination about the anatomical material of the next univel is made at step 174 to see if it is different from the previous or starting univel. Again, this is simply done by using the stored integer position values to examine the anatomical material mapped in array 152 for that univel against the previous univel. The actual points examined are expressed as floats but are only kept track of as integers. Thus, as in table 210 (Figure 7), for the next univel having coordinates of (3.83, 2.5, 6.26) the anatomical material for that univel is stored in the array at (3,2,6) and a comparison between anatomical materials is made against (3,1,5). Similarly, for the univel having coordinates (4.13, 3.5, 6.93) the anatomical material for that univel is stored in the array at (4,3,6).

Because of the eventual possibility that stepping in the primary direction of movement without stepping along the particle track in the secondary direction of movement will cause an error in determining the anatomical material of the univel under examination, at step 172, if the error term exceeds the threshold value, an increase in the

corresponding coordinate value is performed (step 176) to ensure the proper univel is being examined. Thereafter, at step 178, an adjustment of the error terms is performed to account for the increase in the corresponding coordinate value. Although not shown, the error term could also be adjusted to indicate that stepping only occurred in the primary direction of movement. Thence, once adjusted, the determination of the anatomical material of the next univel is made at step 174.

It should be appreciated that the anatomical material of the "next" univel is made in comparison to the starting univel, or, as the movement of the particle is tracked along the particle track, is made in comparison to the previous univel. If, at step 174, the anatomical material is not at least substantially different, the movement of the particle along the particle track is reiteratively traversed to the next univel (step 170) until eventually the particle exits the geometry or intersects with a new material.

Thus, at step 174, if the anatomical material of the next univel is different from the previous or starting univel, a determination is made, at step 180, to see if the particle has exited the geometric model. As in the prior art, if the particle has exited the geometric model, the particle transport simulation is terminated at step 182.

If the particle has not exited the geometric model at step 180 and the anatomical material of the next univel is different from the previous univel, the position of intersection with the new material is determined at step 184. When determined, this position of intersection is reported at step 186 for use in another part of the computer executable instructions.

It should be appreciated from the foregoing that computational time is greatly preserved by stepping through the geometric model in integer based increments because each of the stepping computations and each determination about the anatomical material of each univel is performed by the computer without requiring the use of floating point mathematics. Thus, a medical image having pixels of information in 512 x 512 resolution x 512 axial slices, millions of computations are performed over the course of numerous particles emanated from a radiation source. As described subsequently, this reduction in tracking time has been shown to be at least one order of magnitude faster than any computations heretofore known in the field.

The step 184 for determining where the position of intersection with the new material happens, is further described with reference to Figures 8 and 9. In Figure 8, it is known that in some univel 148, the particle traveling along the particle track entered an anatomical material different from the previous univel. To determine the precise intersection, it is first known that the particle entered the univel 148 along the particle track through one of three planes. The particle may have entered the univel: through the X-Y plane as along particle track 220; through the X-Z plane along particle track 222; or through the Y-Z plane along particle track 224. The X, Y and Z planes being taken in reference to the Cartesian coordinate system depicted. Again, other coordinate systems can be used.

In a preferred embodiment, with reference to Figure 9, three possible intersection points are established along the three primary planes described above, step 190. For example, the first position is 221 along particle track 220. The second position is 223

along particle track 222. The third position is 225 along particle track 224. Since each of these three positions are along a planar surface of a univel, a small epsilon may be added to move each of the three positions inside the univel by a small amount so that ambiguity of being on the planar surface can be avoided for computational purposes.

In a preferred embodiment, the three positions correspond to a floor or ceiling operator. The floor or ceiling is in reference to whether the particle track is moving in positive or negative increments. If positive, a floor is set. If negative, a ceiling is set. An example of this is depicted by particle track 222 in which positive increment advancement occurs in the Y and Z directions and negative increment advancement occurs in the X direction. Then, at step 192, the position where the particle track first enters the new material is determined. This is done by examining whichever particle through one of the three positions first hits or intersects the anatomical material that is different from the previous univel, this is the position of intersection. Again, this intersection position is reported at step 186. Floor and ceiling operators are well known in the art and are not described herein in detail.

With this method of integer based tracking of a movement of a particle along a particle track through a geometric model, it should be appreciated that some univels may be skipped over when tracking the particle. An example of this is shown with reference to Figure 10, wherein a particle track 230, shown only in the X-Y plane, traverses through a small corner of univel 232. As such, if univel 232 is of the same anatomical material as univel 234, there is no need to perform a detailed examination regarding this univel and progression of the particle track can continue to univel 236. Thus, it is only when a

univel has a different anatomical material from the previous univel that any further detailed calculations are required to be made. If the anatomical material of univel 232 is different, but the particle track reenters the original material in univel 236, then an insufficient volume in 234 was intersected to count as a boundary crossing. In the case where the anatomical material of 236 is different than 234, univel 232 will also be examined when determining the precise crossing into the new material since three planes of entry into the new material are considered. Again, when calculations for particle tracks are performed through millions of univels, tremendous computational time is saved.

In contrast to the prior art, it should be appreciated that computational accuracy is improved with more representations of the treatment volume than with fewer. For example, some methods in the prior art used 500 pixels as a single element representation for tracking a particle movement. Yet, in a 256 x 256 resolution, this only equates to about 130 elements in the model. If a particular particle track only passed through a small portion of these 130 elements, an accurate understanding required for computational dosimetry would be severely lacking. Yet here, a 256 x 256 resolution equates to 65,536 univels per axial slice. But because the tracking is performed in integer based increments, the tracking is not only faster but yields more accurate data in the dosimetry planning.

In an alternate embodiment, after step 166 (Figure 6A), a decision 167 is made whether to follow along the particle track or not. When performing Monte Carlo simulation using an alternative scheme known as "boundary elimination," it is only

necessary to know the material of the starting univel and not required to follow along the particle track to determine the next material intersection. Thus, for this alternate method, and for some editing purposes, return is made to the calling program immediately after determining the material of the starting univel. As such, this alternative step is indicated by dashed lines.

With reference to Figure 11, it should be appreciated that as medical imagery becomes even more sophisticated, it is expected that even greater resolutions will be provided, such as in a 1000 pixel x 1000 pixel resolution with 1000 axial slices. Thus, to improve computational times for tracking a particle movement through the geometric model, groupings of elements may be advantageously arranged. One such grouping uses a super univel 250 comprised of an arrangement of smaller univels in a 2 x 2 x 2 configuration. Still other combinations of univels can be effectuated.

Example 1

The following represents data obtained from tracking a movement of 100,000 particles along random particle tracks (Monte Carlo simulated) through a geometric model constructed from a 256 x 256 x 33 medical image consisting of a buffer material, scalp, skull, brain and tumor anatomical materials.

The particle tracks began at a random initial position in the geometric model and traversed in a random direction. Each movement was tracked along the particle track until either the particle intersected an anatomical material different from the anatomical material of the previous univel or was exited from the geometric model. Of the 100,000

particle tracks, 55,137 positions of intersections and 44,863 exits from the geometric model were reported.

Table 1

3,600,422	univels having particle tracks
33,670.034	positions of intersection/ sec
1,212,263.3	univels/ sec
36.004	univels tracked through/ position of intersection reported
2.970	elapsed time (sec)
196,270.562	distance traveled all particle tracks (cm)
66,084.364	distance traveled/ sec

It should be appreciated that since the simulated particle transport was performed in less than about 0.2 hours, the foregoing represents an advance over the present state of the art by as much as 51 times. Heretofore, such simulated particle transport would routinely require as much as 10 hours of computational time or more.

Example 2

The following represents the actual algorithm information used to simulate such advanced particle transport along a particle track as presented at the 1998 Radiation Protection and Shielding Division Topical Conference in Nashville, TN in April. Note that the subject matter of this presentation was directed only to external neutron sources.

Data Initialization: The uniformly spaced medical image data is read into an array. The x-pixel-size, y-pixel-size, and z-pixel size along with the minimum value of

each coordinate is stored so conversions between world coordinates (WC) and normalized array coordinates (NAC) can be easily made. Here, the NAC simply corresponds to a location in the array of univels. For example, any location in the array can be found by an ordered triple of nonnegative integers, i.e., lookup (x,y,z) = array (z (width x length) + y (width) + x). A univel in WC is A mm x B mm x C mm. Whereas the univel in NAC is 1 x 1 x 1, for example.

Parameters: A call to the movement of the particle along a particle track is of the form:

Track_Ray (position_vector, direction_unit_vector, ptr_to_miss_flag, ptr_to_current_region, ptr_to_next_region, ptr_to_distance_to_next_region);

Input to algorithm:

position_vector: Initial position of particle track in WC

direction_unit_vector: Normalized direction of particle track in WC

Output of algorithm:

miss_flag: Either hit a new region or exit the geometric model

current_region: The region (univel) the particle track starts in

next_region: The first region intersected

distance_to_next_region: The distance to the next_region (univel) in WC

Algorithm Initialization Calculations: The initial position and direction must be converted from WC to NAC. The initial anatomical material is stored in current_region. If the particle track does not start inside the univel geometric model, an intersection point with the univel geometric model must be calculated and an artificial starting point is set at this boundary intersection with the outer univel.

Stepping Algorithm: Though the internal routines of the algorithms vary, each is based on using integer arithmetic to find univels that the ideal particle track passes through. Each investigated univel has a corresponding call to a function that looks up the anatomical material type of the univel at the given position. The stepping algorithm terminates when a univel of a new anatomical material type is found or the particle along the particle track exits the geometric model.

Algorithm Completion Calculations: The position of intersection is computed accurately or miss_flag is set to indicate the particle exited the geometric model without an intersection. The distance to this point is calculated in WC and returned in distance_to_next_region. The new material encountered is stored in next_region.

Example 3

The following data was presented at the 1998 conference in Nashville, TN and is exemplary of a particle track having Y as a primary direction of movement, X is the secondary direction of movement increasing in 0.125 units of a Cartesian coordinate system and Z is the tertiary direction of movement increasing in 0.75 units. The initial starting position of the particle track after centering is $x_0 = 5.00$, $y_0 = 1.5$ and $z_0 = 10.125$. Truncating (trunc) is the rounding down function. Stepping along the primary direction

of movement yields the following data with an error term being an integer in the range of -32,768 to 32,767:

Table 2

x	y	z	trunc(x)	trunc(y)	trunc(z)
5.000	1.5	10.125	5	1	10
5.125	2.5	10.875	5	2	10
5.250	3.5	11.625	5	3	11
5.375	4.5	12.375	5	4	12
5.500	5.5	13.125	5	5	13
5.625	6.5	13.875	5	6	13
5.750	7.5	14.625	5	7	14
5.875	8.5	15.375	5	8	15
6.000	9.5	16.125	6	9	16

The bulk of the corresponding stepping algorithm for this example is as follows:

ADDX = 0.125*32768 = 4096

ADDZ = 0.750*32768 = 24576

ADDX_DECERR = ADDX - 32768

ADDZ_DECERR = ADDZ - 32768

ERRX = (x_o - trunc(x_o))*32768 + ADDX_DECERR = -28672

ERRZ = (z_o - trunc(z_o))*32768 + ADDZ_DECERR = -4096

XI = trunc(x)

```
YI = trunc(y)
ZI = trunc(z)

BEGIN_LOOP
  LOOKUP(XI,YI,ZI)
  YI = YI+1
 If (ERRX>=0)
    XI = XI + 1
    ERRX = ERRX + ADDX_DECERR
  Else
  ERRX = ERRX + ADDX
  If (ERRZ>=0)
  ZI = ZI + 1
  ERRZ = ERRZ + ADDZ_DECERR
  Else
  ERRZ = ERRZ + ADDZ
END_LOOP
```

The next table shows the values computed by the algorithm. Notice that the error term, i.e., ERRX or ERRZ, is a pre-computation used to determine how XI and ZI will change in the next iteration, increasing by 1 if the error is greater than or equal to 0 and

remaining the same otherwise. The steps are similar when the directions are allowed to be decreasing.

Table 3

XI	YI	ZI	ERRX	ERRZ
5	1	10	-28672	-4096
5	2	10	-24576	20480
5	3	11	-20480	12288
5	4	12	-16384	4096
5	5	13	-12288	-4096
5	6	13	-8192	20480
5	7	14	-4096	12288
5	8	15	0	4096
6	9	16	-28672	-4096

This example was for each x, y and z increasing and y varying the most. The method would be similar for either x or z varying the most. Negative directions only cause minor complications wherein absolute values of the directions are used to compute the ADDx's. ERRx's are computed based on the distance to the ceiling side rather than the floor side of the initial univel from the initial point.

In the general case, there is some roundoff error since the initial positions and increments may not be expressed exactly as fractions of 32768. Using 32 bit arithmetic instead, an individual error is less than 2^{-31} ($\approx 4.66*10^{-10}$) and the error accumulates by at most that much on each iteration. In a 256x256x40 array of univels, the cumulative error could at worst be $256*2^{-31} = 2^{-23}$ ($\approx 1.19*10^{-7}$) which is insignificant in most cases for two

reasons. The algorithm yields only an approximate x, y, and z as an array position which is then refined to give a precise intersection that is not subject to this cumulative error. Also, the approximated particle movement follows very closely the same univels as the ideal particle track. Being off by at most 2^{-23} of a side length suggests that the approximate particle track reports a position of intersection not intersected by the ideal particle track less than 1 in 1,000,000 times. If the algorithm reports a position of intersection that is not verifiable, the particle movement along the particle track is simply allowed to continue. Any position of intersection distance returned is precise and verified.

The present invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is, therefore, indicated by the appended claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.